特集 ■ プロジェクションマッピング Projection Mapping

Challenges of Projection-Based Augmented Reality Systems in Theme Park Attractions

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1. Introduction

The last decade has witnessed tremendous improvements in display technology. Today's smartphones and laptops offer screen resolutions far beyond what the human eye is able to resolve. TV systems are also in the process of changing to resolutions far beyond "full HD", and cinemas have almost completely transitioned from analog film to digital projection. The high-quality projectors of today's cinema are also well suited for non-standard setups such as, for example, in theme park environments. Generating a scenic lighting environment is one of the most important factors in the overall immersion quality of such attractions, and the usage of digital projectors can help to raise the bar in this regard. It is to be expected that more and more projection systems will be used in the future not only in theme parks, but also for general entertainment, advertisements, and art installations. While the tools have already been developed to enable sufficiently accurate geometric and photometric calibration for content generation of such installations, the question still remains as to whether non-experts will be able to successfully apply and judge calibration, as well as know how to maintain such a complex system without specific knowledge as to its underlying algorithms.

Figure 1
The "Disney Dreams" show at Disneyland Paris uses projectors to turn the whole "Castle of The Sleeping Beauty" and its surrounding into a gigantic show screen.

2. A Quick Introduction to Projection Based Augmented Reality

While already an active research field for several decades, augmented reality（AR）has gained widespread attention over the past few years. For most people today, the term "augmented reality" refers to video see-through AR applications that include perspectively corrected and location-aware graphics or information. Alternatively, projection-based AR belongs to the group of spatial AR technologies in which augmentation is directly visible in space instead on a screen. While this requires more complex system setups compared to, for example, a cell phone with an integrated camera, it offers several interesting applications, such as for building projections, scenic lighting effects, and the superposition of high-quality textures to enhance or alter the appearance of real world surfaces. Prominent examples are given in [2], [3] and [6].

When projecting imagery accurately onto complex-shaped objects, several problems have to be overcome to achieve a convincing impression. Solutions for how to solve such issues will be quickly summarized below (interested readers should see Bimber et. al.'s report [1] for a more detailed overview of the fundamental algorithms).

Figure 2
"The Legend of Captain Jack Sparrow" at Hollywood Studios in Orlando uses projectors to immerse patrons in 360-degree projections on screens, rocks, and a pirate ship.

• **Geometrical Registration:** Projecting onto complex shapes requires the accurate mapping of each individual projector pixel onto a given surface. Most real-world surfaces are far from perfectly flat planes. Imagine, for example, a modern car chassis or natural surface. To accurately project augmented content onto such surfaces, a precise model of the surface geometry has to be attained. This can either be carried out from existing CAD data or other sources, such as laser scanners, or can be directly generated by the projection system by adding cameras to it. Such setups are usually referred to as projector-camera-systems or procams-systems. In these, structured light patterns are projected and captured by the cameras to generate a quick and accurate mapping between individual camera and projector pixels. The most widely used patterns are gray codes or other types of spatially- or color-coded patterns. Depending on the application, the mapping of projector pixels onto a surface can then be carried out by using 2D lookup tables between camera and projector image planes, or by applying full geometric calibration and treating each individual projector as a pinhole device equivalent to a camera (correcting for lens distortion, if required). As the latter enables the accurate registration of projectors into a 3D environment, it has the advantage that the devices can be easily integrated into the content generation pipeline of the installation.

• **Multi-Projector Blending and Shadow Removal:** Depending on the surface complexity, one usually tries to overlap the contributions of multiple projectors, as it may simply not be possible to align multiple projectors so that they do not overlap without any black gaps between projected image edges. Given that light contribution adds up in overlapping areas, though may abruptly drop in the case of shadow casts, the individual contributions of projectors have to be adjusted to equalize reflected intensities with non-overlapping areas. This requires the generation of smooth transitions to avoid the appearance of hard intensity edges in the case of slight misregistrations. Solutions for this problem are presented in [2]. To correct for the non-linear response functions of projectors, which are usually set to sRGB or a similar gamma curve, a radiometric measurement has to be carried out beforehand to linearize its response function.

• **Photometric Calibration and Compensation:** Equalizing the color gamut of multiple projectors [5] as well as neutralizing a surface's varying spatial reflectance [7] requires careful photometric device calibration and compensation image calculation. In addition to the mentioned issues, several specialized methods exist to also compensate for more complex effects such as global illumination, specular reflections, and textures. Some of these approaches deal with individual problems, while others try to solve for all unwanted effects at once [8]. Practically it is sufficient to analyze a system to figure out which illumination effects have the greatest bearing on image quality, and then trying to compensate for each of these individually by using specialized methods adapted for the source of image degradation. Regardless of the setup, diffuse scattering commonly occurs close to surface edges, yet this can be compensated for in various ways as well.

• **Synchronization:** Synchronization is a technical issue that has to be solved to generate a compelling projection. Cameras must be synchronized to projectors in order to capture the correct structured light patterns during calibration. This problem can be solved easily by simply waiting until a pattern is displayed before capturing it. If temporal multiplexing-based projectors are used, such as DLP projectors, care has to be taken to use long enough exposure times in exact accordance with a projector's refresh rate or some multiple of it to avoid color and intensity artifacts. Averaging multiple camera images of the same pattern helps to reduce these artifacts. As soon as multiple projectors are used to present dynamic content, their display refresh timings have to be synchronized with each other to avoid the occurrence of tearing artifacts.

While this is technically possible without any significant problems, it increases the overall complexity and cost of the system.

Depending on the application, not all of the above mentioned points are necessary to generate a satisfactory impression, though focus should be kept on all of them when developing projection-based AR setups. Most of mentioned issues can be solved manually through the use of specific software calibration tools. Particularly when multiple projectors are used in a complex setup, manual tools quickly lead to a cumbersome or even unfeasible process and cameras should be used for automatic system calibration.

Much research has been put into automatically solving the above-mentioned issues with different focuses on image quality or processing speed depending on the application. Methods for geometric calibration can be applied partially in real-time or without any pre-calibration. Blending maps and photometric compensation images can also be calculated for impressive image quality even if non-trivial projection surfaces are used [7].

Despite all these resolutions to various issues, however, one major problem remains: can these fixes be successfully applied in long-term installations operated and maintained by non-expert users within environments that are not perfectly controlled? How can such a system be set up so that high image quality can be achieved reliably while at the same time keeping calibration and maintenance times to a minimum?

3. Challenges of Long-Term Projection Based AR Installations

Several solutions for projection-based AR application calibration issues have been developed, but due to their complexity, many require experts to accurately apply them when setting up a system, adjusting parameters to adapt to noise and other factors in a given setting, and judging the accuracy of a final projection. Aside from these issues that rely on experts to correct, other issues have to be solved for long-term applications, such as entertainment attractions in Disney theme parks. At locations such as these, it typically cannot be expected that operational and maintenance personnel with expertise in computer vision will be present. Therefore, procams systems have to be able to automatically calibrate themselves with little supervision. In addition, these systems have to detect and report potential errors such as hardware defects or other issues that restrict their functionality, such as occluded lines of sight or unexpected lighting situations. Obviously, all of this has to be carried out not only efficiently, but also within a short period of time.

The most crucial factors that have to be solved to generate robust procams systems are listed as follows:

・**Robustness:** Since theme park installations commonly run daily for many hours and are planned to run for several years or even decades, it is required that, independent of any internal or external factors, a procams system be able to provide desired image quality, even in unpredictable situations. If, for whatever reason, satisfactory image quality cannot be achieved, a system has to be able to detect and report this without human intervention.

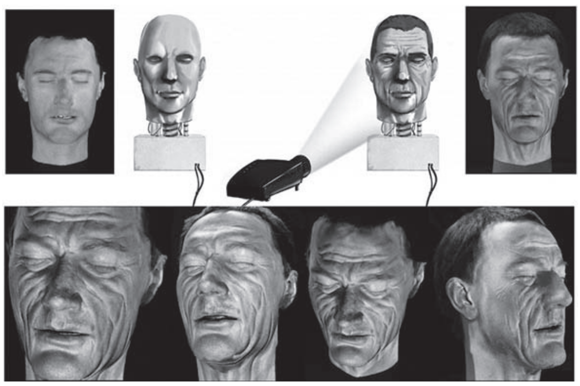

Figure 3
Disney Research Zurich developed a method which uses projection to superimpose high frequency texture details onto an animatronic head to significantly enhance its appearance [6].

・**Accuracy:** The requirements for spatial projection accuracy depend significantly on the setup conditions. Obviously, a large-scale building projection that exists far from observers requires less accurate geometrical registration than a projection of fine details on an animatronic head [6]. Such conditions thus have to be carefully considered when setting up a system and, even more important, attention has to be paid that the variance within consecutive recalibrations required for hardware replacements, cleaning operations and other system restructurations is kept at a relatively low level. As non-experts typically take care of technologies during operational hours and maintenance, automated, self-assessing calibration tools such as camera-based self-calibration can help to assist them.

- **Scalability:** Lab installations typically deal with projectors that are professionally set up for particular experiments in carefully controlled environments. In contrast to this, real-world installations often involve constraints in terms of projector and camera placement, as well as may require more projectors to generate desired pixel coverage— and all of this has to be considered while developing robust calibration algorithms. Optimally, algorithms should not scale more than linearly in terms of processing time and memory requirements. They should, however, enable parallel processing, and, even more important, employ parallel acquisition whenever possible. All cameras, for example, should be able to capture structured light patterns from specific projectors in parallel, and, having already gathered some rough knowledge about the geometrical setup, even non-influencing projectors can project patterns in parallel to speed up acquisition times.
- **Performance/speed:** As the downtimes of everyday projection systems should be kept to a minimum for obvious reasons, calibration and compensation algorithms are required to compute the results as fast as possible. While optimizing calibration processing times in non-real-time applications is not of essential interest within research communities, the duration of these times is a crucial factor in theme park attractions. Therefore, on the one hand, efficient algorithms have to be implemented by excessively using CPU and GPU parallelism whenever possible. On the other hand, processing hardware has to guarantee high bandwidth during acquisition times, as well as enough processing power for computations. As most of the calculations at least linearly scale with the number of projectors used, hardware has to be carefully adapted to offer enough processing resources for the given problem.
- **Maintainability:** Despite having solved for all of the above issues, the question remains as to whether a system can be maintained in a reasonable amount of time and cost-efficiently. The deployment of new technologies is commonly constrained by the fact that keeping maintenance and operational costs as low as possible is a strong requirement in theme park installations. This factor has to be carefully considered when designing new attractions with each of the above-mentioned issues in mind. It is obvious that the more complex the system gets, the more potential sources of error there are. Therefore, a major goal when designing attractions is to find the simplest solution for a system to guarantee desired accuracy given its conceptual and temporal constraints.

4. Conclusions

Projection-based spatial AR is an effective and flexible way to generate dynamic shading effects on complex structured sceneries with a quality that cannot be achieved by only using a large number of standard light sources. This makes this technology quite suitable for scenic entertainment installations, such as those used by The Walt Disney Company in a multitude of their theme park attractions. Some of the attractions in which projectors are used to generate interactive game applications, immersive projections, and complex lighting effects are shown in the figures throughout this document.

Figure 4
“Goofy's Paint'n'Play” at Disneyland Tokyo is an interactive game in which a self-calibrating projector-camera system is used to accurately project virtually shot paint and textures onto walls and furniture.
＊ The color version shown on the frontispiece

The majority of the above-mentioned problems involved in establishing a robust and reliable everyday procams installation can today be resolved by using specialized software tools. The Walt Disney Company developed and still utilizes a procams toolbox framework that offers a set of flexible components that can be individually customized and combined to fit the particular needs of any new installation. However, not every potential problem in projection-based AR has been solved for yet. The following gives a list of outstanding problems:

- **Dynamic projection surfaces:** Projecting onto dynamic objects adds a series of new challenges to projection-based AR, such as real-time scene analysis, low-latency input and output systems, and projection adaptation onto potentially non-rigidly deformable surfaces. It is without question that these issues will significantly complicate a system's design and place much greater limitations on algorithm complexity and runtimes.
- **Low latency:** Even when projecting onto static surfaces, interactive applications require short or even perceptually instantaneous responses so not to distract users. This requires not only a fast processing time, but also a low latency hardware system to give immediate feedback.
- **Complex surface materials:** The projection onto complex materials generating non-diffuse lighting effects like subsurface scattering or glossy reflections requires a much more detailed surface analysis to accurately model the occurring light transport, as well as to compensate for these effects as best as possible given any physical constraints. One recent approach to neutralize these effects is shown in Figure 3, where fine details missing on the skin of an animatronic figure are superimposed by optimized projection images that compensate for subsurface scattering and defocus effects [6].

Overcoming these issues represents a major task for future procams research. While several publications already showed promising results in incipient stages, there is still a long way to go in terms of enabling everyday projection systems to consider and deal with these limitations, but solving these issues would offer a completely new area of interactive projection-based applications. Hopefully researchers all over the world will help to make those procams system happen in the near future.

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【Biography】

Dr. Anselm Grundhöfer is a Senior Research Engineer at Disney Research Zürich, Switzerland, where he works in Dr. Paul Beardsley's computer vision group as technical lead of the Procams Toolbox project. He graduated with a degree in Media Systems Sciences in 2006 and obtained his doctorate in Engineering in 2010 at Bauhaus University, Weimar, Germany. During his studies, he spent several months at the Takemura Lab at Osaka University, Japan.

Anselm's work is mainly focused on developing procams systems and assisting in their deployment, for example, in Disney theme park attractions. Most recently, he is working on multi-projector optimization methods to overcome several unresolved problems involved when projecting onto non-trivial surfaces. Aside from this, he also conducts research on computer vision, AR, video processing, and display technologies.